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STEEL CASTINGS RESEARCH

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PROGRESS REPORT ON RESEARCH PROJECT NO. 37— CORROSION OF CAST STEELS

There is practically no information available to engineers, students and purchasers on the ability of carbon and low alloy cast steel to resist corrosion. All of the information available, prior to the inception of Research Project No. 37, is presented in the Steel Castings Handbook in the form of three tables developed some years ago by the Bureau of Standards on soil corrosion and on water and acid corrosion. It has been assumed that cast steel is corroded to the same extent as wrought steel of similar composition and heat treatment under similar conditions of exposure. Also, it has been indicated that the casting skin on steel castings retards corrosion. However, there was no proof to substantiate either assumption.

The Technical Research Committee recognized the need for data on the corrosion of cast steels, and as a result a research program is now being conducted to compare the corrosion resistance of nine cast steel alloys in marine and industrial atmospheres. The program was focused on corrosion studies for railroad cast steels in connection with the desires of the Third Railroad Corrosion Conference. Exposure tests are being made at the International Nickel Company station at Kure Beach, North Carolina, and at the ASTM industrial atmosphere site at East Chicago, Indiana.

About forty 4 by 6 by ½-inch (beveled edged) specimens were prepared from each of nine cast steel alloys. The chemical composition of the nine alloys is shown in Table I. The surfaces of half of the specimens were subsequently machined, reducing their thickness to ⅜ inch. The specimens

TABLE 1—Composition of Test Steels

Steel No.	Ni	Mn	Cr	V	C	Mo	P	S	Si
1	2.26	0.77	0.19	—	0.17	Trace	0.017	0.021	0.65
2	0.56	0.80	0.60	—	0.26	0.15	.....	.....	0.44
3*	.....	0.87	.....	0.07	0.28	.....	.....	.....	0.42
4	1.08	1.70	.....	—	0.27	.....	0.020	0.023	0.42
5	0.10	0.61	0.21	—	0.14	Trace	0.016	0.026	0.41
6	.....	1.42	.....	—	0.37	.....	0.027	0.022	0.38
7	.....	0.65	.....	—	0.25	.....	0.011	0.021	0.51
8	.....	1.36	.....	0.09	0.37	.....	0.031	0.038	0.34
9**	.....	1.48	.....	—	0.33	.....	0.016	0.025	0.40

*Contains 0.94 percent copper

**5 pounds per ton of high carbon ferro-titanium added to give approximately 0.05 percent Ti

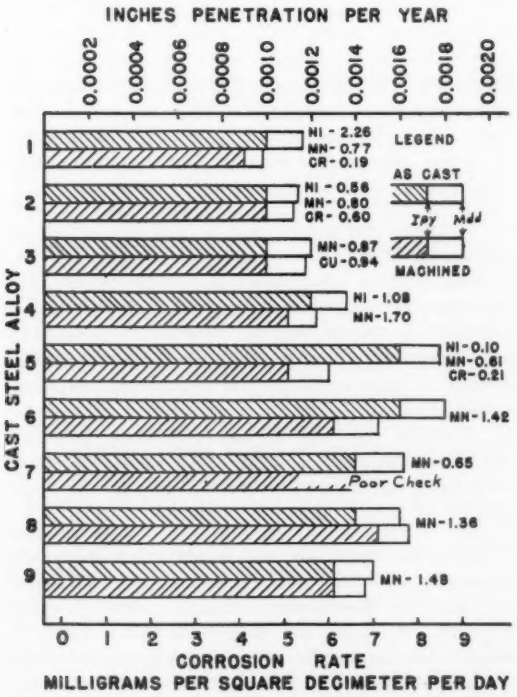

Figure 1—Corrosion rates of machined and as-cast specimens exposed for one (1) year, 800 feet from the ocean.

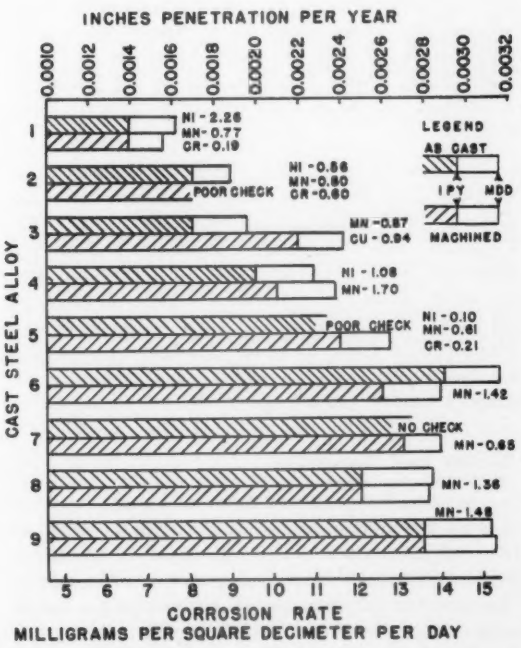

Figure 2—Corrosion rates of machined and as-cast specimens exposed for one (1) year, 80 feet from the ocean.

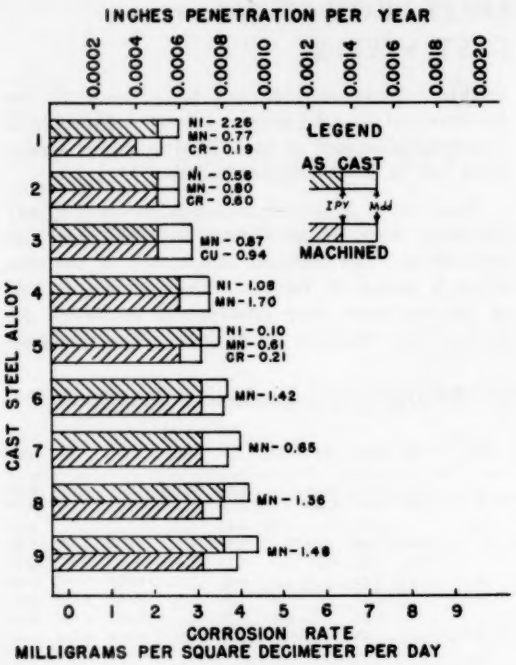

Figure 3—Corrosion rates of machined and as-cast specimens exposed for three (3) years, 800 feet from the ocean.

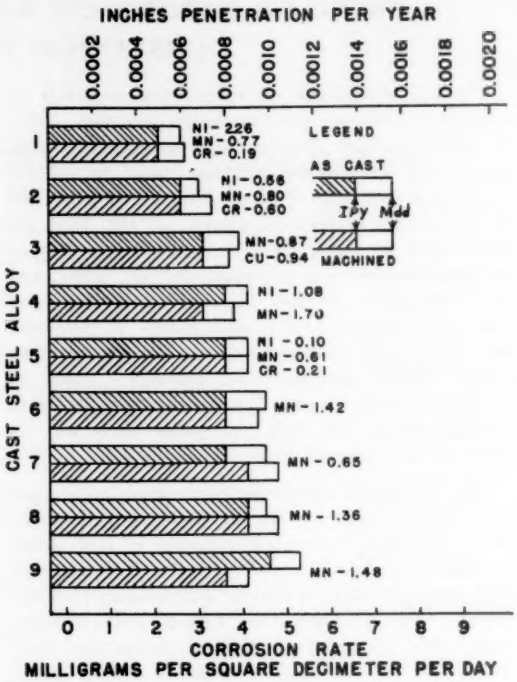

Figure 4—Corrosion rates of machined and as-cast specimens exposed for three (3) years in the industrial atmosphere at East Chicago.

of each composition and surface condition were divided into three groups and exposed in marine atmospheres 80 and 800 feeet from the ocean at Kure Beach, North Carolina, and in the industrial atmosphere at the ASTM site at East Chicago, Indiana.

The specimens at Kure Beach were exposed on October 3, 1953, while the specimens at East Chicago were exposed on November 24, 1953. Duplicate specimens of each composition and surface condition were removed from each exposure site at Kure Beach on October 2, 1954 (363 days exposure), and October 11, 1956 (1104 days exposure), and from the East Chicago exposure site on November 28, 1956 (1100 days exposure), or after 1 and 3 years respectively.

Results and Discussion

The specimens removed from each test site were cleaned by light sandblasting to remove most of the rust and immersed in inhibited hydrochloric acid to remove the remaining rust. This process was repeated on clean control panels and the maximum weight loss due to the cleaning process was found to be 0.3 grams. The weight loss information was converted to corrosion rates in terms of inches penetration per year (ipy) and milligrams lost per square decimeter per day (Mdd). The weight loss due to the cleaning process, 0.3 grams maximum, represents a maximum error in the calculated corrosion rates of 0.1 Mdd or 0.00002 ipy.

Corrosion rates as expressed in Mdd are, of course, obvious in their meaning, i.e., the weight loss for a given surface area (one square decimeter) for an exposure time of 24 hours. Inches penetration per year is merely another method of expressing corrosion rate. This measure of corrosion rate is defined as the depth to which uniform corrosion would penetrate if the material were to be exposed on one side only for 24 hours per day for 365 days. The calculations of ipy values for all specimens were based on the density of mild steel, as the exact density of each composition was not known.

The corrosion rates of as-cast and machined specimens removed from the marine atmospheres at the Kure Beach test site after one (1) year exposure are compared graphically in Figures 1 and 2. Similar comparisons of as-cast and machined specimens removed from all three test sites after three (3) years exposure are shown in Figures 3, 4 and 5.

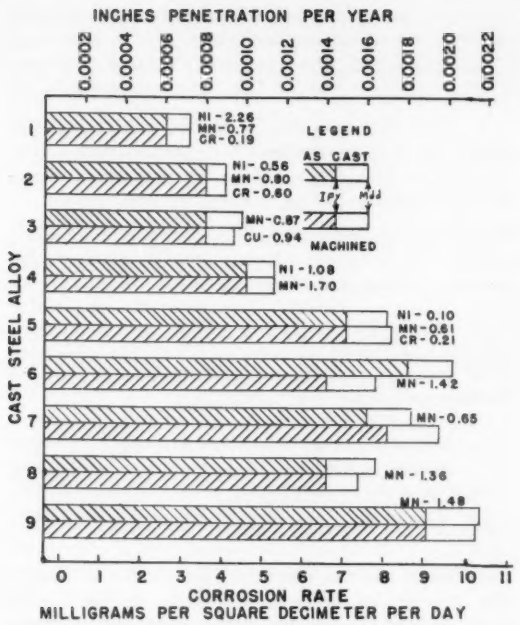

Figure 5—Corrosion rates of machined and as-cast specimens exposed for three (3) years, 80 feet from the ocean.

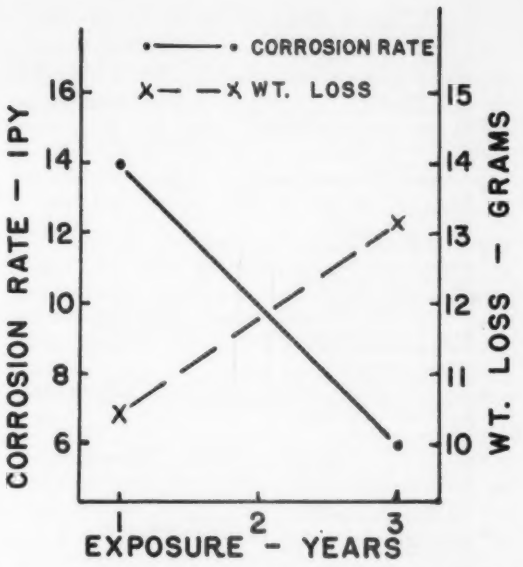

Figure 6—A comparison of the corrosion rate and total weight loss as a function of time showing the protective nature of the scale and rust coating.

The rapid rate of corrosion of the specimens exposed for one year as compared to those exposed for three years is as would be expected. The rate of corrosion decreases as the thickness of rust and scale increase. Thus, the product of corrosive action deposited on the surface of the material acts somewhat as a protective coating. A comparison of the corrosion rate and cumulative weight loss of a typical specimen as a function of exposure time is shown in Figure 6 to illustrate this effect.

The specimens exposed with the surfaces in the as-cast condition were rough prior to exposure making the evaluation of pitting action difficult. The surfaces of all the machined specimens were free of any significant pitting attack.

Figures 1 through 5 indicate that according to this study there is no basis for the assumption that an as-cast surface retards corrosion. The data exhibit no recognizable trend from which a relationship between the corrosion resistance of as-cast and machined surfaces can be drawn. It should be noted that in some cases the data expressed in Mdd show a different relationship between the corrosion rates of as-cast and machined surfaces than the data expressed in ipy. This small discrepancy could be the result of using the density of mild steel rather than the exact density of the material to calculate the ipy corrosion rates.

Figure 7 is a comparison of the corrosion rates (ipy only) of the as-cast specimens exposed in all three test atmospheres for a period of three years. It is obvious from this comparison that the atmosphere 80 feet from the ocean at Kure Beach is more corrosive to all the cast steels included in this study than the other test environments. The industrial atmosphere at East Chicago is shown to be more corrosive to the cast steels studied than the atmosphere 800 feet from the ocean at Kure Beach.

The cast steels containing nickel, manganese and chromium as alloy elements exhibit better corrosion resistance (lower rates of corrosion) than those containing manganese only when exposed in any of the test environments. Increasing the amounts of nickel and chromium alloy increases the corrosion resistance of the cast steel, as would be expected.

A comparison of the corrosion rates of steel Numbers 2 and 4, Figure 7, indicates that the combination of nickel, chromium and manganese as alloying additions are more effective in increasing the corrosion resistance of a cast steel than increased additions of nickel and manganese only. The addition of a small amount of copper apparently increases the corrosion resistance of cast steels containing manganese with no chromium or nickel, see steel Number 3, Figure 7. However, the data are insufficient to justify the establishment of a definite relationship.

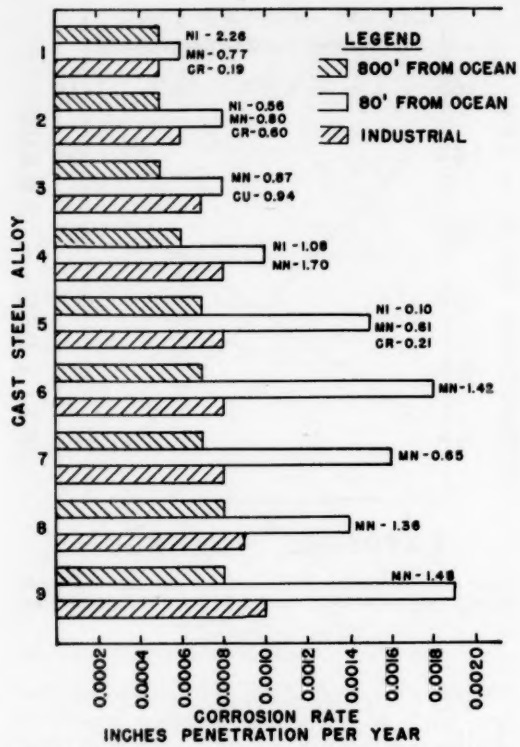

Figure 7—Comparison of the corrosion rates of as-cast specimens exposed in the three test atmospheres for three (3) years.

Conclusions

The conclusions that can be drawn from the data collected after one and three years of exposure are as follows:

1. Machining the surfaces of cast steel specimens of the nine compositions included in this investigation has no significant effect on their corrosion resistance when exposed to any of the test environments.

2. Cast steels containing nickel, manganese and chromium as alloy elements have corrosion resistance superior to cast steels containing manganese alone when exposed in any of the test environments.

3. Increasing the chromium and nickel contents of cast steels containing manganese increases the corrosion resistance in all three test environments.

4. Cast steels containing nickel and manganese only do not exhibit as favorable corrosion resistance as do cast steels containing chromium with reduced amounts of nickel and manganese.

5. Apparently a small amount of copper increases the corrosion resistance of cast steels containing manganese alone or manganese and vanadium. However, the data are not sufficient to justify the establishment of a definite trend.

6. All of the cast steels included in this investigation corroded at a slower rate in the marine atmosphere 800 feet from the ocean than in the other two test environments.

The fastest corrosion rate occurred in the marine atmosphere 80 feet from the ocean.

Disposition:

The research program is being continued with the exposed specimens scheduled to be removed in four years, or after a total exposure period of seven years.

EXCHANGE CHEMISTRY OF BENTONITES AND THEIR INDUSTRIAL APPLICATIONS

*By Arthur G. Clem**

Abstract

Bentonites are all basically montmorillonite, varying only slightly in their chemical compositions. It was thought that perhaps minor variations of exchange ions might influence and help to predict the chemical and physical properties. With this thought in mind, intensive analytical work was done on bentonite from the Belle Fourche area.

Data are presented on the exchange ion of bentonite from varying sections of these same beds, various beds, and varying bentonite producing areas in the commercial zone. The correlation of sodium and calcium ion with its influence on viscosity, green compression strength, dry compression strength and bond properties at elevated temperatures is shown in a general way only.

Introduction

Lumps of bentonite fresh from a deposit offer little or no clue as to their potential application. They must be evaluated by numerous tests to define their potential application. An interesting feature of the bentonite processing industry is that physical tests predominate, and the test conducted to determine the suitability of a bentonite for an application is generally a small scale version of the application itself. The application of a bentonite as a bonding agent is determined by making a foundry sand mixture from

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it and then securing its physical properties. There is, of course, no objection to proving a point in the foundry industry by pouring a test casting into a sand mixture bonded with a new or unusual type of bentonite in order to determine its effectiveness.

For foundry bonding, the bentonites that have moderate strength in the green mix, high strength in the baked and elevated temperature ranges are the sodium base bentonites. The bentonites which have higher strength in the green condition, low strength at time of baking and elevated temperatures are the calcium base bentonites.

Thus, it appeared that a simple check for either sodium content, or calcium content, or the relative percentages of sodium content and calcium content would eliminate a tremendous amount of physical testing. This premise is still sound, but it is more intricate than it appears. Fundamentally, all bentonites contain both sodium and calcium ions. Some are present in the bentonite unit cell itself. Some are present in the form of extraneous salts that were deposited with the bed or washed into the bed after it was formed. Some are present as part of the non-bentonitic impurity.

The approach chosen was that of washing from a bentonite, with a mild stripper solution, the salts which were present in the bentonites as exchange bases and soluble salts. Salts that dissolve in water can affect the physical properties of suspensions of bentonite.

The washing of exchangeable and soluble salts from clay minerals is better known as base exchange; numerous papers have been written on the subject. Briefly, ammonium acetate is generally used as the leaching solution for bentonites, and some preliminary work was done with ammonium acetate solution. However, it was found that the rate of exchange and efficiency of a quaternary ammonium compound, sold commercially as benzyl trimethyl ammonium chloride by Commercial Solvents Company, was excellent and it was used exclusively. It is a clear solution, with a characteristic odor, containing approximately 60 percent BTA chloride by weight and is diluted with distilled water to a 6 percent concentration.

Physical Properties

A cross section of a typical bentonite bed in the Belle Fourche region would be approximately that shown in Figure 1. Under the deepest of overburden, which may range from 25 to 40 feet or more, the bentonite is a deep blue-gray in color, dense, highly compact and with a peculiar sandy texture. As the overburden decreases, the bentonite becomes pale blue in color and changes abruptly to a yellow-green. At the point of color change there is a zone known as the "blue egg" zone in which blocks of bentonite, approximately 8 inches to 12 inches cubed, exist with a thin film of limonite on the surface, yellow-green exterior and a solid, dense, dark blue core. As the overburden becomes shallower, the color becomes more tan and the texture becomes more waxy. Finally, at the point of little or no overburden, the texture becomes coarse-grained again, much like corn meal or thick corn flakes.

The foundry industry is interested in three fundamental properties; green strength, dry strength, and hot strength. Figure 1 shows the relationship of overburden to the bentonite properties. The green compression strength begins high, dips to a moderate point, and then rises slowly again. Dry compression strength is usually an inverse of green compression strength.

Oddly enough, the hot strength, or resistance to load under elevated temperature, closely parallels the water holding capacity; one instance in which a wet property is reasonably related to a bonding property. Hot strength is also plotted in Figure 1.

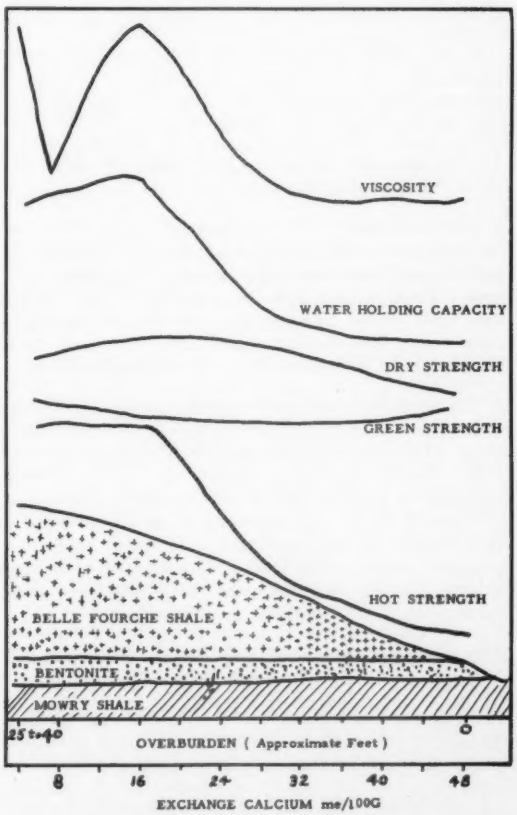

Figure 1—The relationship of the location of a bentonite sample in a bed and its calcium/manganese impurities to all physical properties.

Chemical Properties

The first attempts to evaluate bentonites in terms of their chemical properties dealt solely with the calcium ions. Bentonites from the Wyoming and South Dakota region have reported in the exchange position, sodium, potassium, calcium and magnesium ions. Of these, potassium is minute, on the order of 1 milliequivalent per 100 grams or less. Thus, it was assumed that it would be possible to determine calcium and magnesium alone and calculate the sodium by difference.

The method was very simple; dried bentonites were ground to a powder passing 100 mesh. Ten grams of the powder were mixed with 100 milliliters of 6 percent BTA chloride solution for four minutes with a high speed mixer, then filtered. A portion of the filtrate was checked for total calcium and magnesium ion content by the Versene method which uses the color change of a dye by the chelating of these ions.

The results of this work formed a pattern that is expressed in Figure 1. Apparently there was a definite relation between the degree of calcium and magnesium impurities and the fundamental physical properties of a bentonite.

A great deal of significance was attached to the region of 15 to 20 calcium units since it is roughly the percentage of a bentonite molecule that exists as edge surface ions. The theory was:

1. At one time all bentonites existed in the dense, blue, highly consolidated form.

2. As oxidation and leaching of salts from the covering shale began, calcium ions washed into the bed in combination with sodium, magnesium and iron. Perhaps iron was the catalyst. The calcium ions first tended to congregate at the outside edges, then move into the structure. On this basis, bentonites could be considered in these classifications:

a) Under deep overburden with little or no calcium impurity, the bentonite could exist as discreet single units which would have high water absorption and high viscosity or, more probably, the particles would have a length and width of one molecular dimension, but would have a thickness of 4 to 10 units since the compaction was so great that water could not penetrate between the sheets. As a result of having a large number of thicknesses, with relatively small surface area, the viscosity would be low.

b) As calcium salts washed into the bentonite, the viscosity would hit a minimum as the outside edge of each individual sheet would be covered with calcium ion, discharging the outer edge, but without distorting the particle. This would tend to create a sodium core, calcium veneer bentonite.

c) Further washing of calcium ion into the bentonite bed would tend to create a preponderance of calcium ions at the edges, which in turn would suggest a cross bonding of bentonite units such that more than one would exist in area, with mono-dimensional thickness. The degree of formation of these would be related to the amount of divalent calcium, and the viscosity should rise sharply.

d) Beyond this maximum point further additions of calcium would tend to pry apart the plates and to affix itself to the alumina sheet, turning more and more into a calcium bentonite.

Armed with this basic idea, a random sampling of hundreds of samples of bentonites was undertaken. The exchange calcium and magnesium was determined on a total of 624 samples, and the plotted results against physical characteristics were so thoroughly scattered that no intelligent curve could be drawn from them.

An attempt was made to correlate the values using the Doelman equation for composition, but the attempt proved fruitless. The results were equally haphazard.

Prior to this time it was assumed that all bentonites had an exchange capacity on the order of 85 to 100 units per 100 grams, depending on the moisture content and purity. However, random samples, checked by an outside laboratory for exchange capacity, indicated an ion exchange capacity of 58 to 107 units per 100 grams, and the calcium test would be of no significance unless either the total exchange or the sodium content was known. Therefore, it was decided to determine sodium.

The determination of sodium, potassium and calcium has been greatly simplified recently by the introduction of the flame photometer. It is a simple device that atomizes a solution into a flame, concentrates the color of the flame optically on a suitable filter, and determines the intensity of the color by a photoelectric cell. Properly adjusted, and standardized with simple solutions, it is possible to get direct readings on calcium and potassium and indirect readings on sodium at a rate of one per minute or more.

The Coleman model 21 flame photometer was selected with accompanying Coleman model 6-C spectrophotometer. The extracts to be used in the machine are made of a dry bentonite powder with BTA chloride solution diluted to the level that the machine handles most efficiently and applied in a weak concentration of non-ionic detergent for better atomization.

The divalent ions of calcium and magnesium were converted to percentages of the total dissolved and exchange salts present in a bentonite. It was possible to reduce the scattering of the points within the curve and to achieve curves that were very close to the original prediction. The viscosity curve alone remained distorted. The primary cause for the distortion in this curve was not an error in the fundamental concept, but rather an error due to time and/or structural change.

It was assumed that the maximum viscosity is at a point where 20 percent of the exchange positions are occupied by divalent ions such as calcium and magnesium. If this product is taken from the ground in natural form, bentonite that is high in viscosity is obtained. If it is taken from a supply that has been blended from 10 percent calcium and 30 percent calcium, the flame analysis will show it to be in the proper chemical position for high viscosity, but the sample, since it is a mixture of low viscosity products, will not have high viscosity immediately.

To prove this, low viscosity materials from either side of the optimum peak were selected and checked individually. The viscosity was low. Stockpiling was duplicated by crushing the bentonite to approximately ⅛ inch pellets, moistened to a content of 30 percent and aged in glass jars. Each week an average sample was selected. The material was air dried over the week end, then its moisture was restored with distilled water. This was to duplicate the constant wetting and drying that is obtained in a stored stockpile exposed to the elements.

Within one week, the viscosity had increased substantially. At the end of two weeks, it was half-way to the predicted value. At the end of five weeks, the viscosity had, by actual test, met the curve, and for the next three weeks it was held fairly constant, rising slightly above predictions. Apparently in order to develop viscosity, it is necessary that moisture be present and that the structure change through age.

Practical Application

The foundry bond industry has requirements depending upon the metal that is being cast. These will be discussed briefly.

In steel molding sand, moderate green strength and high hot strength are desired. Steel is poured at relatively high temperatures and occasionally into dried sand molds. Under these conditions a bentonite should have a low percent of calcium impurity for the steel foundry trade. Viscosity is immaterial since the foundry bonding properties are not related to viscosity.

In the gray iron field the high hot strength is not as desirable. In fact, high hot strength and accompanying high dry or baked strength leave portions of the casting with sand firmly baked in place which is difficult to remove, increasing cleaning costs. As a result the most desirable bentonite for this type of work would be that which is past the peak of hot strength, preferably down in the 25 percent to 30 percent calcium impurity range. Quite frequently, the individual foundry chooses to control this property by mixtures of low calcium western bentonite and high calcium southern bentonite.

Research studies, particularly relating percentage of divalent ions to the total, have given us a new concept as to how and why bentonites behave. It is still too early to say definitely, but it is believed that the viscosity is related to the structure and the structure is related to the chemistry of the exchange ions. Other properties appear directly related to exchange chemistry.

It is worth while to note that these data are from Mowry formation bentonites exclusively. It is not known if other formations or mixtures are as predictable.

Conclusion

The physical properties of a Mowry bentonite can be predicted fairly accurately by a knowledge of the leachable sodium and calcium content.

In terms of water absorption, water retention, green, dried, and elevated temperatures bond strength, the properties are associated with the degree of calcium impurity and can be predicted from general curves.

Viscosity is related to impurity, but also to structure. While the viscosity can be predicted with a fair degree of accuracy from a knowledge of the impurity, the structure can be determined only by further work with X-ray analysis.

BENTONITE SPECIFICATION

The Steel Founders' Society's Specifications Committee recently prepared a preliminary draft of a specification for the purchase of western bentonite. The bentonite producers reviewed the specification at a joint meeting of the Specifications Committee and the bentonite producers held the latter part of March. A revised version of the specification is now being prepared, including the changes in testing methods suggested at the meeting.

The Society is arranging for the production of a standard Liquid Limit test kit to be used in conjunction with the specification. The equipment is similar to that used for soil testing but will include several modifications. The cooperation of the industry is requested with regard to postponing work with the Liquid Limit test until the standard equipment and procedure are available. The success of the bentonite specification is dependent upon the standardization and reproducibility of testing results which, in turn, are dependent upon standardized equipment and procedures.

LOW TEMPERATURE PROPERTIES OF LOW AND MEDIUM ALLOY STEEL CASTINGS

*By G. M. Michie and W. J. Jackson**

This report constitutes the continuation of studies on Low Temperature Properties of Steel Castings—Carbon Steels, the results of which were reported in the Journal of Steel Castings Research, No. 7, January, 1957.

The purpose of this investigation was to establish data on the low temperature impact properties of low and medium alloy steel castings, as commercially supplied. The following types of cast steels were examined:

- 1½ percent manganese
- 1½ percent manganese-molybdenum
- 1¼ percent chromium-molybdenum
- 3 percent chromium-molybdenum
- 4 percent nickel
- 1½ percent nickel-chromium-molybdenum
- 2½ percent nickel-chromium-molybdenum

The test material was supplied by six foundries in the form of either keel blocks or cloverleaf castings; six such castings being supplied from each of three separate heats.

Particulars of the test material, insofar as steelmaking, deoxidation practice and form of test blocks are concerned, are given in Table I. Chemical analyses of the steels tested are shown in Table II.

Heat Treatment of Test Material

Details of the heat treatments used are given in Table III and IV, together with test data. The heat treatments were, in all cases, preceded by an annealing treatment. The various heat treatments were applied with the following aims in view:

1. To determine the differences in impact properties between material in the normalized and tempered condition, and in the quenched and tempered condition.
2. To determine the differences in impact properties between material which has been air cooled from the tempering temperatures and material which has been water quenched from the tempering temperature.
3. To determine the effect on the impact transition curves of tempering the quenched steels to different hardness levels.

Testing Procedure

Charpy V-notch impact specimens were prepared from material in each of the conditions of heat treatments. All notches were machined in a direction parallel to the nearest casting surface (i.e., in general, at right angles to the columnar crystal growth).

Testing was performed on a Mohr and Federhoff machine which has a striking force of 30kg.m. and a striking velocity of 5.3 meters per second. The V-notch specimens were broken over a range of temperatures sufficiently wide to permit construction of the full transition curves.

Results of Impact Tests

The original report used four arbitrary criteria for comparison of the low temperature properties, namely, the temperature to give:

1. the 10 foot-pound impact level
2. the 15 foot-pound impact level
3. the "mean energy", i.e., the temperature at which the energy absorbed is the mean of the energies corresponding to the toe and the peak of the transition curve.
4. the 50 percent fibrous, 50 percent brittle fracture level.

TABLE I—Manufacturing Particulars of Steels Investigated

Material Code	Process	Deoxidation and Finishing Additions (pounds/ton)	Casting Form
F	Converter	3-FeSi, 2-Al, 2-FeTi	Keel Block
G	B.H.F.*	1½-CaSiMn, all to ladle 2.24-Al (0.1%) to ladle	Cloverleaf
H	Converter	3-FeSi, 2-Al, 2-FeTi	Keel Block
I	B.E.A.**	1½-CaSiMn, all to ladle	Cloverleaf
J	B.E.A.	1½-Al, 2-CaSi to ladle two additions of FeSi 2-Al to ladle	Cloverleaf
K	B.E.A.	FeSi, FeMn	Cloverleaf
L	B.H.F.	2½-Al, to ladle 13-FeSi, 10½-FeMn 4-Al to ladle	Keel Block
M	B.E.A.	Two additions of FeSi	Cloverleaf
N	B.H.F.	2-Al to ladle 7.8-CaSi (0.35%) to ladle	Cloverleaf
O	B.H.F.	15-FeSi, 11½-FeMn 3½-Al to ladle	Keel Block
P	B.H.F.	6-FeSi, 6-FeMn, 3-Al to ladle	Keel Block
Q	B.H.F.	10-CaSi	Cloverleaf

* Basic High Frequency

** Basic Electric Arc

*The British Steel Casting Research Association, Sheffield, England.

TABLE II—Chemical Analysis of Low and Medium Alloy Steels

STEEL	C%	Mn%	S%	P%
1¼% Mn				
F	0.21-0.24	1.52-1.80	0.022-0.028	0.043-0.056
G	0.23-0.25	1.45-1.55	0.043-0.046	0.022-0.024
1½% Mn, ¼% Mo				
H	0.28-0.31	1.38	0.020-0.030	0.044-0.047
I	0.23-0.25	1.29-1.38	0.012-0.014	0.024-0.027
J	0.30-0.31	1.35-1.46	0.015-0.021	0.016-0.021
1¼% Cr, ½% Mo				
K	0.28-0.31	0.67-0.91	0.012-0.016	0.019-0.024
L	0.30-0.31	0.48-0.51	0.036-0.041	0.022-0.023
1½% Ni, ½% Cr ¼% Mo				
M	0.27-0.32	0.66-0.76	0.013-0.026	0.013-0.020
2½% Ni, ¾% Cr ½% Mo				
N	0.29-0.34	0.51-0.74	0.013-0.014	0.015-0.020
4% Ni				
O	0.08-0.10	0.55-0.60	0.030-0.038	0.019-0.020
3% Cr, ½% Mo				
P	0.16-0.17	0.39-0.60	0.032-0.042	0.022-0.024
Q	0.24-0.27	0.44-0.76	0.020-0.032	0.019-0.022

NOTE: Si contents between 0.25-0.50 percent.

TABLE III—Effect of Heat Treatment at Essentially Constant Hardness for Each Type of Steel

Steel	Material Code	Heat Treatment	BHN	Impact Energy at -40°F (Ft/lb)	Transition Temperature†
1½% Mn	F	N + a.c.	168	12	+63
	F	WQ, a.c.	178	13	+36
	F	WQ, w.q.	174	21	—10
	G	WQ, w.q.	158	18	—10
1½% Mn-Mo	H	WQ, a.c.	192	27	—26
	I	N + a.c.	193	9	+109
	I	NN, a.c.	198	12	+36
	I	WQ, w.q.	264	38	—45
1¼% Cr-Mo	K	AC, f.c.	159	7	+113
	K	WQ, a.c.	188	51	—67
4% Ni	O	WQ, a.c.	170	23	—55
	O	WQ, w.q.	176	22	—62

WQ = Water Quenched from 1560 to 1700°F

N = Normalized

NN = Double normalize

a.c. = Air cooled from tempering temperature

w.q. = Water quenched from tempering temperature

†Temperature to give 50 percent fibrous fracture

The temperature associated with a 50 percent fibrous fracture, for the sake of simplicity, is the only criterion of those listed above that is rpeorted here. The impact energy associated with a testing temperature of minus 40 degrees F was taken from the complete transition curves and is also reported here as a more comprehensive basis of comparison.

The effect of heat treatment on the impact properties at essentially a constant hardness level for each type of steel is summarized in Table III. The effect of tempering quenched steels to different tensile levels is shown in Table IV.

It should be noted that some comparisons cannot be considered valid. For example, neither of the treatments on steels I or K should be used to directly compare the effect of normalizing and tempering with quenching and tempering because they were tempered to different hardnesses.

Discussion of Results

It should be appreciated at the onset that this investigation was not planned or conducted primarily with a view of comparing one steel composition against another. To enable such a comparison to be drawn, it would have been necessary to prepare all the test material under conditions in which the influence of such variables as steelmaking process, deoxidation practice and impurity content (sulfur and phosphorus) were each under control. This was not possible at the time, and in any case the purpose of the investigation was to establish low temperature property levels obtainable in commercial practice, rather than those obtainable in steel manufactured under strictly comparable conditions. For this reason, the comparison between different types of steels which has been drawn in Table IV should be interpreted only with the greatest care.

Attention is drawn to the superior properties of steel K when quenched and tempered to a nominal 110,000 psi tensile level, Table IV. This steel was the only one supplied for this investigation in the form of cloverleaf test bars (see Table I), that is, heat treatment was performed on a smaller sectional thickness compared to the other steels. The faster cooling rate during quenching, therefore, may have influenced the impact test results.

Test bar castings from the same heat were subjected to the various heat treatments for the investigation of the effect of type of heat treatment and the effect of tensile level on quenched steels, thus eliminating the variables of chemical composition and

steelmaking practice. For example, using the 1½ percent manganese steel F, the improvement in quenching and tempering over normalizing and tempering was established, as shown in Table III.

It is generally acknowledged that certain steels are susceptible to temper brittleness, and that even if tempering is carried out at temperatures above a critical range, slow cooling through this range will result in temper embrittlement. The influence of water quenching from the tempering temperature, as compared with air cooling, was therefore determined on the 1½ percent manganese steel F and the 4 percent nickel steel O. The summarized results in Table III show that water quenching the 1½ percent manganese steel after tempering develops better low temperature properties than air cooling after tempering. A similar, but much smaller, improvement is exhibited by the 4 percent nickel steel. This is to be expected as nickel alone has a smaller temper embrittling influence than manganese.

The improvement in double normalizing and tempering over single normalizing and tempering is illustrated by the treatments which were carried out on the 1½ percent manganese-molybdenum steel I.

As an additional illustration of the advantage of quenching and tempering over normalizing and tempering, the results for steel I are shown in Table III. It will be appreciated that a direct comparison between the normalized and tempered and quenched and tempered samples of steel I is unjustified because of their different tensile levels, but since the effect of tempering to a high tensile level is to raise the transition temperature, the improvement demonstrated by quenching would have been even greater had the material been tempered to the 110,000 psi tensile level.

Table IV illustrates primarily the effect on low temperature properties of tempering various quenched steels, to different tensile levels. By reference to Table IV, it will be seen that, in general, transition temperatures are raised by increasing the tensile level (hardness). It was also found that at the higher testing temperatures, maximum impact values are lowered.

In an attempt to assess for each different steel the influence of changing hardness, the shift of the 50 percent fibrous fracture transition temperature was expressed in terms of the temperature change per 50 points increase in hardness (BHN). No consistent relationship was apparent, the shift in temperature sometimes being in the direction of an increase, and sometimes a decrease.

TABLE IV—Effect of Tempering to Various Tensile Strength Levels

STEEL	Material Code	Heat Treatment	UTS (psi)	BHN	Impact Energy (-40°F)	Transition Temperature (°F)
1½% Mn	G	WQ+w.q.	88,000	158	18	—9
	G	WQ+w.q.	110,000	183	13	—35
	H	WQ+a.c.	88,000	179	26	—17
	H	WQ+a.c.	110,000	192	27	—26
1½% Mn-Mo	H	WQ+a.c.	132,000	279	13	+54
	I	WQ+w.q.	132,000	264	38	—40
	I	WQ+w.q.	165,000	323	24	—24
	J	WQ+w.q.	132,000	255	41	—103
	K	WQ+a.c.	110,000	188	51	—69
1¼% Cr-Mo	L	WQ+a.c.	110,000	195	28	—90
	L	WQ+a.c.	132,000	280	18	—56
	L	WQ+a.c.	165,000	350	10	—71
1½% Ni-Cr-Mo	M	OQ+w.q.	110,000	198	39	—90
	M	OQ+w.q.	132,000	253	30	—58
	M	OQ+w.q.	165,000	297	15	+34
2½% Ni-Cr-Mo	N	OQ+a.c.	110,000	244	50	—141
	N	OQ+a.c.	120,000	270	39	—128
	N	OQ+a.c.	165,000	346	27	—80
4% Ni	O	WQ+w.q.	88,000	176	22	—63
	O	WQ+w.q.	110,000	185	21	—58
3% Cr-Mo	P	OQ+a.c.	110,000	191	20	—37
	Q	OQ+a.c.	110,000	180	39	—58
	Q	OQ+a.c.	132,000	267	12	+30

OQ=Oi quenched from 1600 to 1650°F.

A comparison using the shift of the impact energy transition curves would have been complicated by the associated change in maximum impact values. To overcome this difficulty therefore, a measurement was made of the area bounded by the curves themselves and the lines joining the lowest temperature points on each curve where 100 percent ductile fracture and 100 percent brittle fracture occurred. Again, no consistent relationship could be detected. Other attempts to relate the shift of either the impact energy or the fracture appearance transition curves to a cause factor (e.g., hardness or tempering temperature) met with no success. It appears therefore, that if a transition curve of a quenched and tempered steel is known, the transition curve resulting from the use of a different tempering temperature cannot be predicted at the present time.

Conclusions

1. Based upon notched bar impact tests, comparisons have been drawn between the low temperature properties obtained on various commercially produced low and medium alloy steels, cast in test block form. The results are summarized in Tables III and IV.

2. The influence of heat treatment upon low temperature impact properties was investigated, and the results permit the following conclusions to be drawn:

a) In the case of the 1½ percent manganese and the 1½ percent manganese-molybdenum steels, quenching and tempering gave better results than normalizing and tempering.

b) In the case of the 1½ percent manganese steel, which is a composition susceptible to temper embrittlement, the advantage of quenching over normalizing was marked when the steel was quenched from the tempering temperature. Little advantage was gained by quenching the low carbon, 4 percent nickel steel from the tempering temperature.

c) In the case of the 1½ percent manganese-molybdenum steel, a treatment consisting of double normalizing and tempering did not result in any marked improvement as compared with single normalizing and tempering.

d) The general effect of decreasing the tempering temperature (increasing tensile level) of quenched steels was twofold, namely, (i) to lower the maximum impact value, and (ii) to raise the transition temperature.

3. Strictly speaking, the work described does not permit the low temperature properties of the various alloy steels to be compared on the basis of chemical composition, per se. The superior properties shown by steels tested in the fully hardened and tempered condition, draw attention however to the importance in this respect of the influence of composition on hardenability. It is evident that optimum properties can only be secured in low and medium alloy steel casting for low temperature service, provided the alloy content of the steel is sufficient to ensure that, using the quenching facilities available, a fully hardened structure is obtained throughout the casting sections involved.

JAPANESE INVESTIGATIONS OF HOT TEARING

The Journal of the Iron and Steel Institute of Japan recently published papers by Susumu Oki, Nippon Rolling Stock Co. and Hideo Nagashima, The Hitachi Ltd., reporting the results of studies of the influence of chemical composition of cast steel on hot tearing tendency. A vertical cylinder, with four horizontal and radial branches, and a plate casting were used as test castings. The conclusions obtained from the studies on the influence of C, Si, Mn, P and S were reported as follows:

1) The hot tearing tendency increases as the carbon content increases in the range of 0.16 to 0.60 percent.

2) Steels containing 0.4 to 0.5 percent silicon exhibited the maximum resistance to hot tearing, although no simple correlation between silicon content and hot tearing tendency was determined.

3) The hot tearing tendency decreases as the manganese content is increased above 0.75 percent.

4) Small increases in phosphorus are almost as detrimental to the hot tearing resistance as a similar increase in sulfur; an increase in phosphorus from 0.02 to 0.04 percent having nearly the same effect as an increase in sulfur from 0.01 to 0.02 percent.

5) Sulfur was found to have the most pronounced effect on the hot tearing tendency with a very small increase in sulfur reducing the resistance to hot tearing appreciably.

The influence of aluminum on the hot tearing tendency was investigated when an increase in the occurrence of hot tears in large steel castings accompanied an attempt to eliminate pin hole porosity by increasing the deoxidizing aluminum addition from 0.6 to 1.2 pounds per ton. The increased aluminum addition eliminated the porosity but the number of tears in large, dry sand molded castings immediately increased. No evidence of an increase in tearing was noted for small green sand molded castings. The increased hot tearing tendency was directly traced to the increased addition of aluminum but no mention was made of the inclusion type involved.

It is interesting to note the comparison between the Japanese studies and those performed by Mr. J. A. Rassenfoss of American Steel Foundries, as reported in Steel Foundry Facts, Issue Number 120, March, 1952. In general the conclusions of the studies are the same. However, Mr. Rassenfoss concludes that the hot tearing tendency decreases as the carbon content is either increased or decreased from the 0.25 percent level. Mr. Rassenfoss also goes further than the Japanese in analyzing the effect of aluminum in producing elongated Type II inclusions which increase the hot tearing susceptibility. The effect of Type II inclusions, together with the effect of other factors, on the hot tearing tendency is also discussed in SFSA Research Report No. 38, Elements of Design for Prevention of Hot Tearing in Steel Castings.

OPTIMUM OPERATING PROCEDURE FOR BASIC ELECTRIC STEEL FURNACE FOR DESULFURIZATION AND DEPHOSPHORIZATION

*By John Zotos**

The purpose of this investigation is to evaluate the effect of process variations in order to develop an optimum operating procedure for producing a high quality, low sulfur, low phosphorus steel in a six and one-half-ton basic-electric furnace.

The equipment used in this investigation was a nine-foot-diameter, Swindell electric arc melting furnace of the swing-roof, top-charging design, with a basic lining, and a melting capacity of 10,000 to 13,000 pounds.

Procedure

Three types of steel totaling eleven heats were produced while compiling the data for the development of the optimum procedure submitted herewith. The three steels are: high nickel 4325, 4140, and 4330.

The initial procedure used in heat number 1 was based on a 10,000-pound scrap steel charge and was as follows:

1. The charge consisted of the scrap, 200 pounds of limestone, and 40 pounds of powdered coke. The limestone and coke were loaded into the furnace after a thin scrap layer lined the bottom, and the remaining scrap was added. The densest scrap was placed directly under the electrodes, and the lighter part of the scrap was evenly distributed throughout the furnace.

2. Meltdown commenced with a power input of 1900 kilowatts and a voltage of 120 volts, drawn from the 3000 KVA transformer.

3. After the formation of a metal pool, the power input was increased to 3000 kilowatts and the voltage increased to 180 volts. These values were maintained until complete meltdown was realized.

4. At complete meltdown, the voltage was returned to 120 volts, and the power input was regulated to maintain a bath temperature of 2850 degrees F to 2950 degrees F.

5. The first metal test specimen A was taken and analyzed for carbon, manganese, silicon, chromium, molybdenum, nickel, sulfur and phosphorus.

6. A controlled addition of 400 pounds of dry iron ore and 100 pounds of limestone, pre-mixed together, was added over a 45 minute period, so that oreing could commence.

7. One hour after meltdown, the first slag (meltdown slag plus oxidizing slag) was removed through the slag door with the aid of steel skimmers.

8. After the first slag-off, metal test specimen B was taken for carbon, sulfur and phosphorus analyses.

9. The wash slag consisting of 100 pounds of limestone and 35 pounds of dry fluorspar was added to the bath.

10. One hour later, the results of metal test B were received, and the slag was completely removed.

11. After the slag-off, the reducing slag consisting of 200 pounds of limestone, 70 pounds of fluorspar, 10 pounds of sand and 20 pounds of powdered coke, pre-mixed together, was added to the bare bath.

12. At the shape-up of the reducing slag, metal test specimen C was taken for carbon, sulfur and phosphorus analyses.

13. The appropriate nickel, chromium and molybdenum additions, based on the analysis of metal test specimen A, were made in the form of ferroalloys.

14. One hour after the shape-up of the reducing slag, and upon receipt of the analysis of metal test C, the required carbon addition was made in the form of carborite, a sintered carbon-scrap steel mixture.

15. Upon complete solution of the carborite, the power input was raised again to bring the bath up to the desired pouring temperature.

16. The manganese and silicon additions, based on metal test A, were made in the form of ferroalloys, and the molten steel was maintained at the tapping temperature.

17. The final metal test specimen D was taken for a complete analysis, and the heat was tapped into a bottom pour ladle.

18. Ten pounds of aluminum were added to the ladle during the tapping operation.

Procedure Changes

The only change in the entire procedure for heat number 2 was the basicity of the slags. The limestone additions to the slags were increased to 300 pounds to the charge slag, 150 pounds to the ore

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slag, 120 pounds to the wash slag, and 260 pounds to the reducing slag. The increased basicity of the slags was used to improve dephosphorization and desulfurization.

Pebble lime replaced limestone additions in all slags and calcined coke replaced powdered coke additions in heat number 3. The charge slag contained 160 pounds of lime and 40 pounds of coke. The meltdown slag was removed before adding the oreing slag to aid in the elimination of sulfur and phosphorus.

The lime additions were 160 pounds to the oreing slag, 80 pounds to the wash slag, and 160 pounds to the reducing slag. The reducing slag sand addition was increased to 15 pounds. Lime was used in this heat to shape up the slags quickly and thus reduce the heat time.

Heat number 4 was changed from heat number 3 only by the addition of three (3) pounds of aluminum after the wash slag was completely removed.

Heat number 5 was similar to number 4 except that ten pounds of ferrosilicon were added to the bath in place of the three pounds of aluminum. Also, the amount of calcined coke in the reducing slag was doubled to aid the formation of a carbide-rich, reducing slag.

Incorporated in heat number 6 were several changes. The slag-off after meltdown first adopted in heat number 3 was eliminated, and limestone replaced lime in all slags. In addition, 30 pounds of carborite were added to the bare bath, along with the ten pounds of ferrosilicon, after the complete removal of the wash slag, and 20 pounds of powdered coke replaced the 40 pounds of calcined coke in the reducing slag. These new changes were made to further aid deoxidation of the steel before the reducing period commenced; to aid in the formation of calcium carbide for adequate desulfurization; and to eliminate the high-sulfur calcined coke from the reducing slag, thus increasing the slag's sulfur-holding capacity. The new slag compositions were: a) 300 pounds of limestone and 50 pounds of calcined coke in the charge slag; b) 400 pounds of dry iron ore and 150 pounds of limestone in the oreing slag; c) 150 pounds of limestone and 35 pounds of dry fluorspar in the wash slag; and d) 300 pounds of limestone, 60 pounds of fluorspar, 15 pounds of sand and 20 pounds of powdered coke in the reducing slag.

Heat number 7 incorporated one major change, namely: the application of mechanical agitation to intermix the slag and metal during the reducing period, thus aiding desulfurization. In addition, definite time limits were set on all slags and were as follows: a) The charge slag was held on for 20 minutes after meltdown before the addition of the ore slag commenced; b) The oreing slag was held on for 75 minutes before its removal took place; c) The wash slag was kept on for 45 minutes before its removal, and d) The reducing slag was held on for 80 minutes after it had shaped up. Also, the alloy additions in this heat were based on the analysis of metal test specimen C, rather than on that of metal test specimen A as was the case in heat numbers 1 through 6. This latter move improved the metallurgical control.

Heat number 8 incorporated the last major changes in the melting procedure. Ninety pounds of ferrosilicon, 60 pounds of ferromanganese and 30 pounds of carborite were added to the bare bath after complete removal of the wash slag had taken place, and five pounds of fine ferrosilicon were mixed in the reducing slag. The additions were made to insure complete deoxidation of the steel before commencing with the reducing period.

Standard Operating Procedure

At the conclusion of heat number 8, the furnace capacity was increased to 12,000 pounds. The following standard operating procedure was established for producing steel under optimum conditions of desulfurization and dephosphorization. Incorporated therein were the changes introduced in heat numbers 2 through 8.

1. The charge consisted of 12,000 pounds of scrap, 400 pounds of limestone and 50 pounds of calcined coke. The limestone and coke were loaded into the furnace after a thin layer of scrap lined the bottom, and the remaining scrap was added to this.

2. Meltdown commenced with a power input of 1900 kilowatts and a voltage of 120 volts.

3. After the formation of a metal pool, the power input was increased to 3000 kilowatts and the voltage was raised to 180 volts. These values were maintained until complete meltdown was realized.

4. At complete meltdown, the voltage was again returned to 120 volts, and the power input was regulated to maintain a bath temperature of 2850 degrees F to 2950 degrees F.

5. A 20 minute waiting period followed during which the bath was rabbled several times with the aid of steel skimmers.

6. Metal test specimen A was taken and analyzed for carbon, manganese, silicon, chromium, molybdenum, nickel, sulfur and phosphorus.

7. A controlled addition of 480 pounds of dry iron ore and 200 pounds of limestone, pre-mixed together, was added over a 45 minute period, so that oreing could commence.

8. One hour after the oreing period started, the first slag (meltdown slag plus oxidizing slag) was removed through the slag door with the aid of steel skimmers.

9. After the first slag-off, metal test specimen B was taken for carbon, sulfur and phosphorus.

10. The wash slag consisting of 180 pounds of limestone and 42 pounds of dry fluorspar was then added to the clean bath.

11. Thirty minutes later the wash slag was completely removed. During this period, the bath was rabbled several times to produce good intermixing of slag and metal.

12. After the second slag-off the reducing slag was added in the following sequences:

a) Ninety pounds of ferrosilicon, sixty pounds of ferromanganese and ten pounds of carborite were added.

b) Upon complete solution of components added in a), the pre-mixed slag consisting of 360 pounds of limestone, 60 pounds of dry fluorspar and 15 pounds of fine ferrosilicon was added.

c) When this slag became molten, powdered coke amounting to 30 pounds in total was added at various intervals and intermixed with the slag by rabbling the bath. This aided in the formation of calcium carbide to promote optimum desulfurization.

d) Varying amounts of limestone, fluorspar, ferrosilicon and coke were added at intervals to properly shape up the slag. The bath was rabbled several times, and a bath temperature of between 2900 degrees F and 2950 degrees F was maintained to assure optimum operating conditions.

13. After the reducing slag had shaped up, metal test specimen C was taken for a complete analysis (same as Step 6).

14. Upon receipt of the analysis of metal test C, the appropriate nickel, chromium, molybdenum and carbon additions were made in the form of ferroalloys.

15. Upon complete solution of these alloy additions and approximately 90 minutes after the shape up of the reducing slag had taken place, the power input was raised again to bring the bath up to the desired pouring temperature.

16. The manganese and silicon additions, based on metal test C, were made in the form of ferroalloys, and the molten steel was maintained at the tapping temperatures.

17. The final metal test specimen D was taken for a complete analysis, and the heat was tapped into a bottom pour ladle.

18. Twelve pounds of aluminum were added to the ladle during the tapping operation to assure complete deoxidation.

19. The desired castings were then poured.

Results and Discussions

The results of the eleven steel heats processed in the six and one-half ton, basic-electric steel furnace, obtained while compiling the data for the development of the standard operating procedure using optimum condition of desulfurization and dephosphorization, are illustrated in Table I.

An analysis of the carbon content variation throughout the heat indicated that the carbon losses of the steels ranged from 0.30 to 0.55 percent during the oxidizing period, while the residual carbon for each heat ranged between 0.02 to 0.05 percent. The carbon content remained constant throughout the wash slag period, but increased towards the desired values during the reducing period. This increase is a result of the carbon additions made to the steel bath, after receiving the result of metal test C, to adjust the carbon level in the finished steel. All the heats produced, with the exception of heat number 6, have carbon values that fall within the desired range. The results of heat number 6 show a carbon content of 0.35 percent, approximately 0.03 percent less than the minimum acceptable value. This came about from the addition of the carborite to the steel bath at a temperature of 3100 degrees F, 200 degrees above the recommended operating conditions. The normal carbon addition was inadequate as a result of the super-heated conditions.

The molybdenum and nickel analyses had final values which fell within the desired range and were controlled very accurately during each heat.

The chromium analysis of heat numbers 1 through 6, shown in Table I indicates a substantial deviation from the desired analysis range. The reason for this discrepancy is the fact that the chromium addition in these six heats was based on metal test A, taken before the oxidizing period commenced. This resulted in an estimated chromium loss during the

TABLE I—The Analyses of The Steel Produced in Heats One Through Eleven in The Six and One-Half Ton Basic-Electric Furnace (Steel Composition in Percent)

Heat No.	Type Of Steel	C	Mn	Si	Cr	Mo	Ni	S	P
1	4325	0.25	0.78	0.30	0.45	0.43	2.38	0.034	0.008
2	4325	0.26	1.00	0.37	0.46	0.44	2.27	0.032	0.009
3	4325	0.23	1.03	0.44	0.69	0.49	2.40	0.027	0.010
4	4140	0.43	0.99	0.55	1.01	0.23	.....	0.027	0.008
5	4140	0.39	1.03	0.40	1.15	0.23	.....	0.021	0.010
6	4140	0.35	1.08	0.55	1.11	0.21	.....	0.019	0.006
7	4140	0.40	0.89	0.35	0.96	0.22	.....	0.024	0.008
8	4140	0.43	0.80	0.19	1.07	0.25	.....	0.013	0.012
9	4330	0.29	0.96	0.23	0.96	0.37	2.04	0.005	0.007
10	4330	0.31	0.94	0.20	0.88	0.36	2.02	0.012	0.011
11	4325	0.26	1.50	0.45	0.92	0.45	2.45	0.010	0.012

oxidizing period which varied from heat to heat and could not be given a specific value. Better control of the chromium analysis resulted in heat numbers 7 through 11 because the chromium addition was based on metal test C, taken after the oxidizing period had ceased. This allowed better metallurgical control on the final chromium content in the steels produced.

Manganese and silicon analyses in the steels produced also deviated from the desired analysis range for heat numbers 1 through 6. This discrepancy again is due to the fact that the manganese and silicon additions during these heats were based on metal test A taken before the oxidizing period commenced. The manganese and silicon losses during the oxidizing period did not remain constant from heat to heat. Thus, a specific manganese or silicon addition could not be made to compensate for these losses, and a variation in analysis resulted. In heat numbers 7 through 11, the manganese and silicon additions were based on metal test C taken during the reducing period, and resulted in better control of the final manganese and silicon content of the steels produced. Heat number 11 shows a manganese content of 1.50 percent and a silicon content of 0.45 percent, values exceeding the desired analysis range. The reason for this discrepancy in heat number 11 is the incorrect weighing of the alloy additions.

The sulfur and phosphorus contents of the steel produced in eleven basic-electric heats are illustrated in Figure 1.

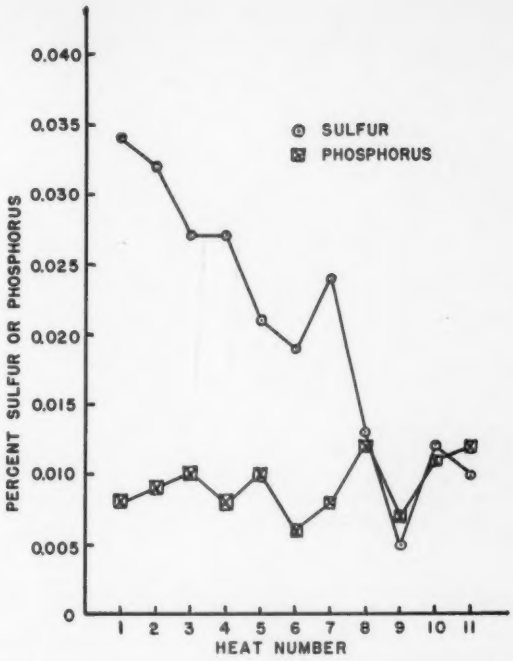


Figure 1—Sulfur and phosphorus content of steels produced in eleven basic electric heats.

The sulfur content of heat number 1 had a high value of 0.034 percent. An analysis of the variation of the sulfur contents during the processing of the heat shows that the sulfur content of this heat increased from a value of 0.025 percent sulfur to the final value of 0.034 percent, indicating that no desulfurization took place during the entire heat.

Heat number 2, which incorporated an increase slag basicity in the procedure, showed a slight drop in sulfur by containing 0.032 percent in the final product. The initial sulfur content in this steel was 0.042 percent, indicating that the desulfurizing effect in this heat was good.

Heat number 3 had a meltdown sulfur content equal to 0.026 percent. There was no change in the sulfur content during this heat, even though lime was used in the slags in place of limestone to see what effect this would have on the desulfurizing power of the slags.

In heat number 4, the addition of three pounds of aluminum to deoxidize the steel bath after the complete removal of the wash slag did not have too much of a major effect in reducing the sulfur content of the steel.

Heat number 5 incorporated the addition of ten pounds of ferrosilicon to the bath just before commencing the reducing period. This resulted in the removal of sufficient sulfur to attain a final content of 0.021 percent.

Heat number 6 incorporated the addition of 10 pounds of ferrosilicon and 30 pounds of carborite to the bare bath. The sulfur content of this heat had an initial value of 0.020 percent. It rose to a value of 0.033 percent at the start of the reducing period and was reduced to a value of 0.019 percent sulfur in the finished product, indicating good desulfurization conditions existed during the reducing period of this heat. This shows that adequate deoxidation of the steel bath before commencing the reducing period is a necessary factor for good desulfurizing action between reducing slags.

Heat number 7 confirms the results of number 6 by removing 0.011 percent sulfur during the reducing period.

Heat number 8 incorporated the addition of 90 pounds of ferrosilicon, 60 pounds of ferromanganese and 30 pounds of carborite to the bath, after complete removal of the wash slag, to assure a low oxygen level in the steel before commencing the reducing period.

The results show that after starting with a sulfur content of 0.025 percent, the final value attained was 0.013 percent indicating good desulfurization.

Heats 9 through 11 were operated under the developed standard operating procedure and the results are clearly illustrated in Table I. Heat number 9 had a meltdown sulfur content equal to 0.028 percent. During the oxidizing and wash period, the sulfur content was reduced to 0.025 percent. The reducing period in this heat saw the removal of 0.020 percent sulfur to attain a final value of 0.005 percent. This indicates that ideal conditions for good desulfurization existed during the reducing period of this heat.

In heat number 10, the initial sulfur content was 0.024 percent. The oxidizing period saw a rise in the sulfur content to a value of 0.029 percent, but the combined results of the wash and reducing periods reduced the steel's sulfur analysis to a value of 0.012 percent. This result again indicates that adequate desulfurization existed during the refining of this heat.

Heat number 11 had a meltdown sulfur value of 0.023 percent. The sulfur content of this final heat remained constant during the oxidizing period. The combined effect of the wash and reducing periods lowered the level of the sulfur content to 0.010 percent, again displaying good desulfurization during the refining period of this heat.

The results of heat numbers 9 through 11 indicate that in using the developed standard operating procedure, adequate deoxidation of the steel occurred before reducing slag was charged, and sufficient calcium carbide was present in the reducing slag, resulting in optimum desulfurization.

Figure 2 illustrates the variations between the sulfur content of the steels produced in seven basic-electric heats with the change in percent iron oxide contained in the reducing slags. If the assumption is made that the greater the percent iron oxide present in the reducing slag, the higher the oxygen level in the steel bath, then the hypothesis discussed previously —that optimum desulfurization is obtained at low oxygen levels—is fully confirmed by the results.

The average phosphorus content of all the scrap charges was approximately 0.025 percent. The average phosphorus loss during the oxidizing period of these heats was approximately 0.019 percent. These results show that the oxidizing procedure used in all heats was adequate for removing the bulk of the initial phosphorus content. The average phosphorus percentage decreased slightly during the wash period but began to rise during the reducing periods of all the heats. The average rise in the phosphorus content during the reducing period was approximately 0.003 percent and could be accounted for as being present in the alloy additions made during this refining period. The average value, however, of the final phosphorus contents of heats 1 through 11 was approximately 0.010 percent, which indicated optimum dephosphorization conditions existed during each of these heats.

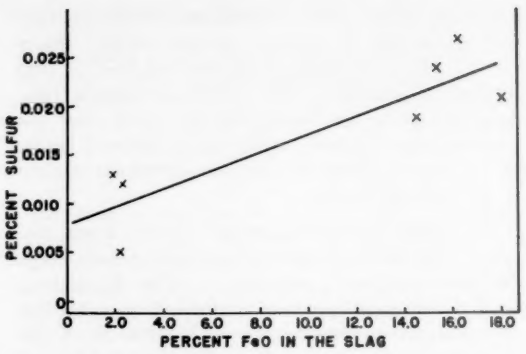


Figure 2—The relationship between the percent iron oxide in the reducing slag and the sulfur content of the steels produced in the first seven heats.

The whole investigation revealed that the systematic change of parameters of the operation results in the development of a standard procedure, which produces optimum steels such as High Nickel 4325, 4330 and 4140. It may be expected that a similar procedure can be adapted to produce as many other grades of steel as desired under optimum conditions of desulfurization and dephosphorization, following the method of investigation carried out in this thesis.

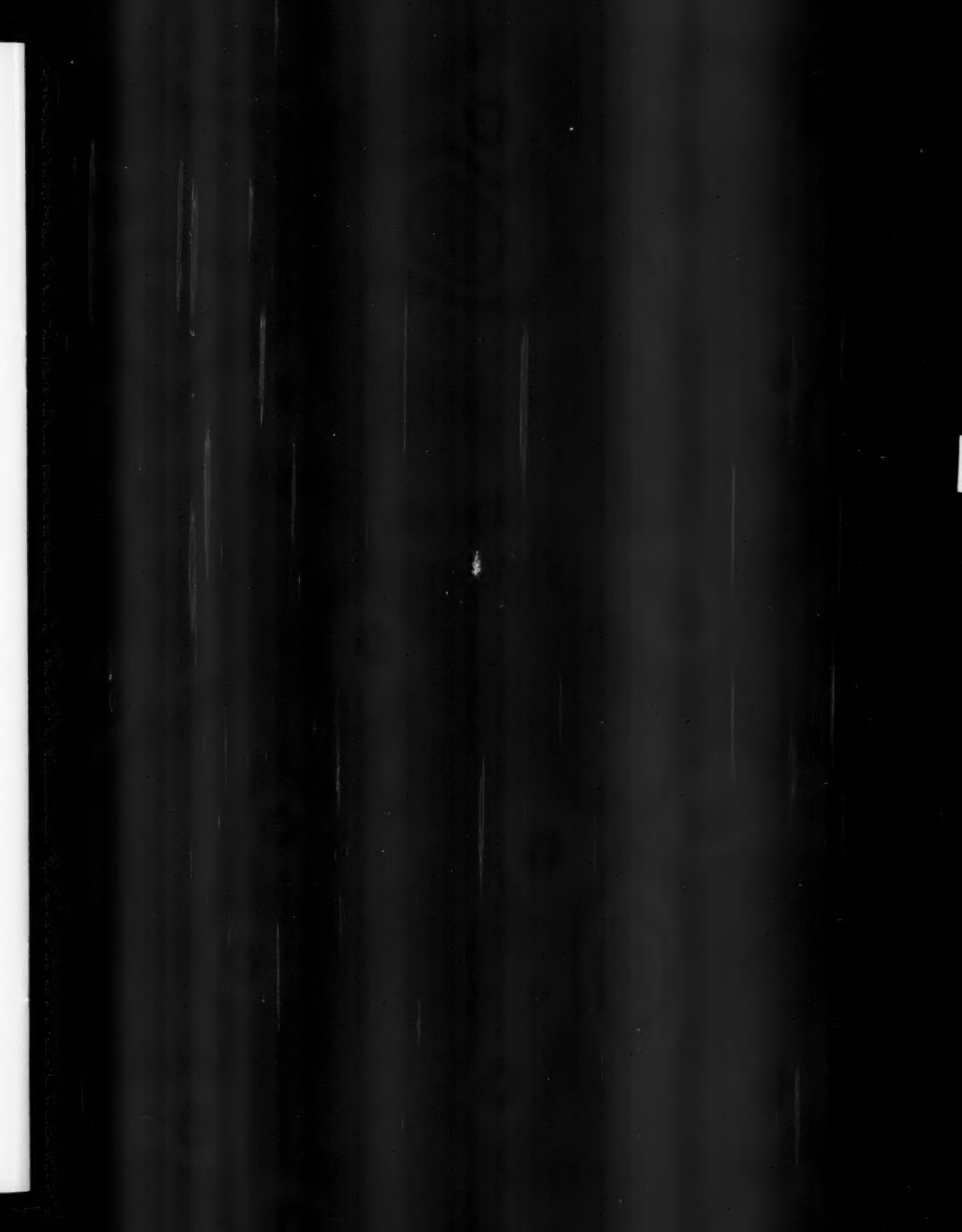
Conclusions and Recommendations

In conclusion, optimum conditions of desulfurization and dephosphorization prevail in the production of basic-electric steels if the following conditions exist:

1. High slag basicity and adequate slag volume during the oxidizing wash and reducing periods.

2. Adequate carbon content at meltdown and sufficient iron oxide additions during the oxidizing period (approximately 12 pounds of iron oxide to remove one pound of carbon) to assure a good boil and adequate dephosphorization.

3. Sufficient deoxidation of the steel bath before commencing the reducing period.

4. Adequate powdered coke additions to the reducing slag to assure the proper amount of calcium carbide for optimum desulfurization.

5. Proper temperature control to assure a bath temperature of between 2850 degrees F to 2950 degrees F during the oxidizing period, and 2900 degrees F to 2950 degrees F during the reducing period.